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Evaluation of Digital Optical Method To Determine Plume Opacity during Nighttime

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United States Environmental Protection Agency (USEPA) set opacity standards for visual emissions from industrial sources to protect ambient air quality. USEPA developed Method 9, which is a reference method to describe how plume opacity can be quantified by human observers during daytime conditions. However, it would be beneficial to determine plume opacity with digital still cameras (DSCs) to provide graphical records of the plume and its environment during visual emission evaluation and to be able to determine plume opacity with DSCs during nighttime conditions. Digital optical method (DOM) was developed to quantify plume opacity from photographs that were provided by a DSC during daytime. Past daytime field campaigns have demonstrated that DOM provided opacity readings that met Method 9 certification requirements. In this paper, the principles and methodology of DOM to quantify plume opacity during nighttime are described. Also, results are described from a nighttime field campaign that occurred at Springfield, IL. Opacity readings provided by DOM were compared with the opacity values obtained with the reference in-stack transmissometer of the smoke generator. The average opacity errors were 2.3–3.5% for contrast model of DOM for all levels of plume opacity. The average opacity errors were 2.0–7.6% for the transmission model of DOM for plumes with opacity 0–50%. These results are encouraging and indicate that DOM has the potential to quantify plume opacity during nighttime.

Introduction

Particulate matter (PM) in the atmosphere raises public concerns because of its adverse effect on public health (*1*). PM also degrades ambient visibility (*2*). United States Environmental Protection Agency (USEPA) developed emission standards for sources that emit PM into the atmosphere to protect public health and welfare, one of which is a plume opacity standard. Opacity is defined in the Code of Federal Regulations (*3*) as "the degree to which smoke and/or particulate matter emissions reduce the transmission of light and obscure the view of an object in the background".

The primary method used to quantify plume opacity is Method 9 (*4*), which relies on the visual perception of certified human observers to determine plume opacity. To be certified according to Method 9, a human observer needs to achieve an accuracy by having individual opacity errors (IOE, d_i) ≤15% and average opacity errors (AOE, $\bar{d}$) ≤7.5% for both groups of black and white plumes during a smoke school test. Method 9 has an extensive history of successful applications but has been questioned about its subjectivity (*5*). In addition, Method 9 was developed for daytime conditions with limitations for the sun's orientation with respect to the observer and the plume (i.e., the plume shall be observed with the sun located in the 140° sector to the back of the observer). However, industrial sources can emit plumes during nighttime, which can be seen with ancillary lighting. Therefore, plumes emitted during nighttime should also be readily characterized for opacity. Several State regulatory agencies have recognized the need of nighttime quantification of plume opacity by participating with nighttime visual emission smoke school certification (e.g., CA, AK, AZ, and NV) and nighttime visual emission monitoring in their respective states. For example, the California Air Resources Board uses a Method 9-based technique for nighttime conditions to determine the opacity of plumes generated by stationary sources, ships, and wood burning fireplaces (*6*). Protocols to quantify plume opacity through visual observations during nighttime have also been proposed in Colorado (*7*). Also, Hawaii and Alaska use a non-EPA-approved visual emission method that is performed by humans to measure the opacity of plumes that are generated by residential wood smoke chimneys at night (*8*).

Lidar is an EPA approved alternative to Method 9 to quantify plume opacity (*9*). Ambient aerosol's optical properties such as extinction and backscatter have also been measured during nighttime using Raman lidar (*10*). Use of a lidar's high-energy narrow-band laser enables active remote sensing of plumes independent of ambient lighting conditions and, hence, allows measurement during daytime and nighttime hours. However, lidar is an expensive instrument whose price can be >$100,000 USD. Despite its high cost and complex operation, its capability of nighttime operation make Method 9 the preferred method to measure plume opacity in the atmosphere.

Digital still photography has also been used to characterize atmospheric optics during nighttime. A digital still camera (DSC) was used to determine the atmosphere's optical thickness by taking pictures of stars during nighttime. DSC measurements were combined with lidar measurements to provide extinction-to-backscatter ratios of atmospheric aerosol (*11*).

Digital still photography has also been used successfully during the daytime to quantify plume opacity. For instance, the digital opacity compliance system (DOCS) was developed to quantify plume opacity using a specific digital camera that self-calibrates for clear-sky background (*12*). DOCS was tested with clear skies at a high mountain desert, cloudy skies with mild temperature and moderate wind, and overcast skies with freezing temperature and light rain that was mixed with snow (*12*). Most recently, DOCS was tested using a range of commercially available cameras in lieu of a specific digital camera that was required to be used for the previous field campaigns (*12*). Another DSC-based method, digital optical method (DOM), was developed from light transfer principles to quantify plume opacity using commercial-off-the-shelf digital still cameras (*13*). Testing during daytime demonstrated that DOM provided results that are consistent with Method 9 requirements (*14*). There are many similarities between Method 9 and DOM: (a) both methods detect the

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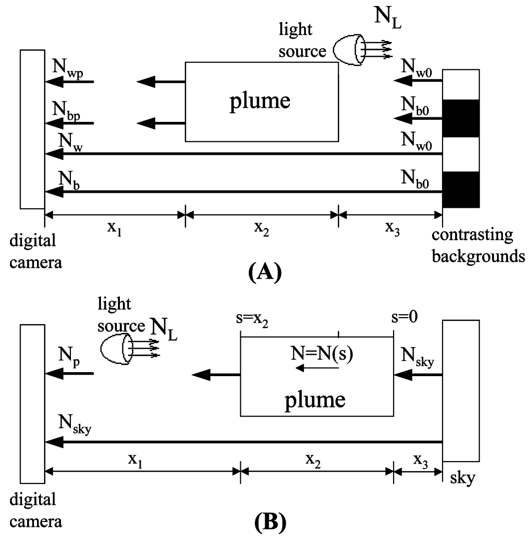


FIGURE 1. Schematic describing the contrast model (A) and the transmission model (B) to determine plume opacity during nighttime.

plume and its background with a photosensitive device (e.g., DOM uses the CCD inside the camera while Method 9 uses the retina of human eyes); (b) both methods quantify plume opacity by analyzing the image acquired by the photosensitive device (CCD or retina, e.g., DOM uses a computer while Method 9 uses a human's brain); and (c) both methods measure the opacity of the plume in the ambient environment that is outside of the stack. However, there are also differences between DOM and Method 9. For example, Method 9 quantifies plume opacity with the sun located in a 140° sector behind the observer (i.e., daytime conditions), while DOM has the capability to determine plume opacity during daytime *and* nighttime, and Method 9 does not provide a digital image of the plume and background to document the event, whereas DOM provides such documentation.

This study reports on the development and use of digital still photography to quantify plume opacity during nighttime. Principles about how DOM quantified plume opacity during nighttime and the results from field-testing of this method are described below.

Methodology. DOM quantifies plume opacity using either the contrast model or the transmission model, which have been described in detail for daytime opacity measurements (*13, 15*), but is described here briefly for clarity. The contrast model quantifies plume opacity by viewing the plume in front and next to a background that has areas in contrast with each other (e.g., black and white areas). Plume opacity is then determined based on the observed change in contrast of the background areas that are behind and next to the plume. The contrast between two specified areas is then determined from the ratio of radiances coming from those areas. The transmission model quantifies plume opacity by viewing the plume in front of a background that is in contrast to the plume (e.g., a clear sky for black or white plumes or a white cloudy sky for black plumes). Plume opacity for either model is then based on the ratios between the radiances from the plume and its background. However, the DSC does not measure radiance values directly. The ratio of radiance values is determined by the corresponding pixel values available from the digital image. Opacity value is then calculated from the pixel values using the resulting analytical equation from either the contrast model or the transmission model as described below.

The contrast and transmission models were further developed as described here to quantify plume opacity during nighttime. The nighttime-based contrast model requires that the contrasting background is set behind and next to the plume and sufficient light is available to illuminate the background for a DSC to obtain a digital image of the plume and its background over a reasonable time period (e.g., $^{1}/_{8}$ s). The plume can scatter and/or absorb the incident light from its background, which results in light extinction. The contrast model considers the transmission of light from the background that is illuminated by the light source, N_L, as the light passes through the plume (path length x_2) and through the ambient atmosphere (path lengths $x_1 + x_3$) (Figure 1A).

N_{w0} and N_{b0} are radiance values directly emitted from the bright and dark areas of the contrasting background, respectively. N_{wp} and N_{bp} are the radiance values from N_{w0} and N_{b0} after attenuation by the ambient atmosphere and the plume along path lengths x_1, x_3, and x_2, and detected by the DSC as pixel values. N_w and N_b are radiance values from the bright and dark areas of the contrasting background, respectively, as detected by the DSC as pixel values after attenuation of light caused by the plume-free atmosphere between the background and camera (i.e., path lengths $x_1 + x_2 + x_3$). The radiance values received by the camera are then expressed as

$$N_{wp} = [(N_{w0} \times T_3^* + N_3^*)\,T_p^*\,T_2^* + N_2^* + N_p^*]\,T_1^* + N_1^* \quad (1)$$

$$N_{bp} = [(N_{b0} \times T_3^* + N_3^*)\,T_p^*\,T_2^* + N_2^* + N_p^*]\,T_1^* + N_1^* \quad (2)$$

$$N_w = [(N_{w0} \times T_3^* + N_3^*)\,T_2^* + N_2^*]\,T_1^* + N_1^* \quad (3)$$

$$N_b = [(N_{b0} \times T_3^* + N_3^*)\,T_2^* + N_2^*]\,T_1^* + N_1^* \quad (4)$$

where T_1^*, T_2^*, T_3^*, and T_p^* are transmittances of the atmosphere along paths x_1, x_2, and x_3, and of the plume, respectively. N_1^*, N_2^*, N_3^*, and N_p^* are path radiances of the atmosphere along paths x_1, x_2, and x_3, and of the plume, respectively. From eqs 1 and 2,

$$N_{wp} - N_{bp} = (N_{w0} - N_{b0}) \times T_1^* \times T_2^* \times T_3^* \times T_p^* \quad (5)$$

From eqs 3 and 4,

$$N_w - N_b = (N_{w0} - N_{b0}) \times T_1^* \times T_2^* \times T_3^* \quad (6)$$

From eqs 5 and 6,

$$T_p^* = \frac{N_{wp} - N_{bp}}{N_w - N_b} \quad (7)$$

According to the definition of opacity, $O = 1 - T_p^*$, where O stands for opacity. Therefore, the contrast model describes plume opacity by

$$O = 1 - \frac{N_{wp} - N_{bp}}{N_w - N_b} \quad (8)$$

The transmission model considers the transmission of light from the sky toward the camera as it passes through the ambient atmosphere (path lengths x_1 and x_3) and through the plume (path length x_2) before detection of the light by the camera (Figure 1B). N_L is the radiance value from the controlled light source. N_{sky} is the radiance value from the sky. N_p is the radiance value from N_{sky} after attenuation by the ambient atmosphere along path lengths x_1 and x_3, and the plume along path length x_2 as detected by the DSC. The nighttime-based transmission model requires only the dark sky as the background while the plume is directly illuminated by the controlled light source for the camera to obtain the digital image of the plume and its dark-sky background over a reasonable time period (e.g., $^{1}/_{8}$ s). Under this situation, the plume scatters the incident light that is detected by the camera. The change of the controlled light source's radiance that is directed toward the camera over a differential distance,

ds, through the plume is then described by eq 9 according to the radiative transfer equation (*15*):

$$\frac{dN}{ds} = -\sigma_s N - \sigma_a N + \sigma_a B(T) + \frac{\sigma_s}{4\pi}\int_0^{2\pi}\int_{-1}^{1} N_{sky} P(\theta)\,d\mu\,d\varphi + N_L \frac{P(\theta)}{4\pi}\omega\sigma_e + S_0 e^{-\tau/\mu_0}\frac{P(\theta)}{4\pi}\omega\sigma_e \quad (9)$$

Where N_L= radiance from the light source; N = radiance at coordinate s; s = horizontal coordinate; μ = cos(zenith angle); ϕ = azimuth angle; N_{sky} = radiance from the sky background; $\sigma_s = \sigma_e \cdot \omega$, scattering coefficient; $\sigma_a = \sigma_e \cdot (1-\omega)$, absorption coefficient; $\sigma_e = \sigma_s + \sigma_a$, extinction coefficient; ω = single scattering albedo; $B = B(T)$, thermal emission factor; T: temperature; $P = P(\theta)$, phase function; θ = scattering angle; S_0 = solar constant; τ = optical depth of the atmosphere; μ_0 = cos(solar zenith angle)

Radiances at visible wavelengths are of interest here. Hence the thermal term ($\sigma_a B(T)$) is neglected. Tests occurred during the nighttime, which allowed the solar term

$$S_0 e^{-t/\mu_0}\frac{P(\theta)}{4\pi}\omega\sigma_e$$

and its diffusive scattering term

$$\frac{\sigma_s}{4\pi}\int_0^{2\pi}\int_{-1}^{1} N_{sky} P(\theta)\,d\mu\,d\varphi$$

to be neglected. Therefore, eq 9 becomes

$$\frac{dN}{ds} = -\sigma_e N + N_L \frac{P(\theta)}{4\pi}\omega\sigma_e = -\sigma_e(N - J) \quad (10)$$

where

$$J = N_L \frac{P(\theta)}{4\pi}\omega \quad (11)$$

Separation of variables and integration of eq 10 using the boundary conditions ($N = N_{sky}$ at $s = 0$, and $N = (N_p - N_1^*)/T_1^*$ at $s = x_2$), and assuming the plume is uniform along the light source's path within the plume result in

$$\frac{\frac{N_p - N_1^*}{T_1^*} - J}{N_{sky} - J} = \exp(-\sigma_e x_2) \quad (12)$$

The path radiance of the atmosphere (N_1^*) along path x_1 is considered negligible compared to the radiance from the illuminated plume. In addition, the transmittance of the atmosphere along path x_1 (T_1^*) is assumed to be 1 when x_1 is <50 m. This assumption is based on the following calculation:

Conditions: the mean (±standard deviation) total light scattering coefficient for aerosol particles (as measured at the Bondville Environmental Aerosol Research Site, which is located 134 km away from Springfield IL) is $26.9 \pm 28.3\ Mm^{-1}$, an average single scattering albedo of 0.91, a Rayleigh scattering coefficient of the atmosphere of $13.2\ Mm^{-1}$ at sea level, negligible absorption of visible light by gases, and a path length of 50 m.

The resulting transmittance of the atmosphere is $T_1^* = \exp[-(26.9 \times 10^{-6}/0.91 + 13.2 \times 10^{-6}) \times 50] = 0.998$, which is very close to 1.

However, this assumption will be invalid if the path extinction >2% when the camera is further from the plume (e.g., $x_1 > 500$ m) and/or the ambient atmosphere's extinction coefficient is very large (e.g., $\sigma_e = 4 \times 10^{-4}\ m^{-1}$). Therefore, eq 12 becomes

$$O = \frac{\frac{N_p}{N_{sky}} - 1}{\frac{J}{N_{sky}} - 1} \quad (13)$$

The ratio N_p/N_{sky} can be determined from the corresponding pixel values from the digital photograph of the plume and its background (*14*). So only the parameter J/N_{sky} needs to be determined to quantify plume opacity. However, the parameter, $J/N_{sky} = (N_L/N_{sky})(P(\theta)/4\pi)\omega$, which is referred to as "K" hereafter, is a function of N_L, plume type ($P(\theta)$, ω), and ambient lighting (N_{sky}). So K can be theoretically calculated only when all the above conditions are known. However, this parameter can be determined empirically from a photograph of a plume with known opacity under typical field settings. For example, with a photograph of a plume that is 50% opaque, the radiance ratio between the plume and sky, $N_{p50\%}/N_{sky}$ can be determined by means of the camera response function (*15*). Then the calibrated value for K can be determined by inverting eq 13:

$$K = \frac{1}{50\%}\left(\frac{N_{p50\%}}{N_{sky}} - 1\right) + 1 \quad (14)$$

Once the parameter, K, is calibrated using plumes with known opacity (e.g., 50%) and eq 14, the opacity of any other plumes can be quantified based on the radiance ratio between the plume and sky (N_p/N_{sky}) and the calibrated parameter, K, using eq 13.

The performance of the contrast and transmission models was evaluated by comparing their reported opacity values to the opacity values from the reference in-stack transmissometer of the smoke generator. The individual opacity errors (IOE, d_i) and average opacity errors (AOE, $\bar{d}$) for both groups of black and white plumes during a smoke school test were calculated and reported in this paper to demonstrate the accuracy of DOM during nighttime applications. In this study, IOE is defined with unit of percent as the absolute difference between an opacity value, $O_{1,i}$, that was obtained by a DSC observation, and a corresponding opacity value, $O_{2,i}$, that was measured by a reference in-stack transmissometer, as described by

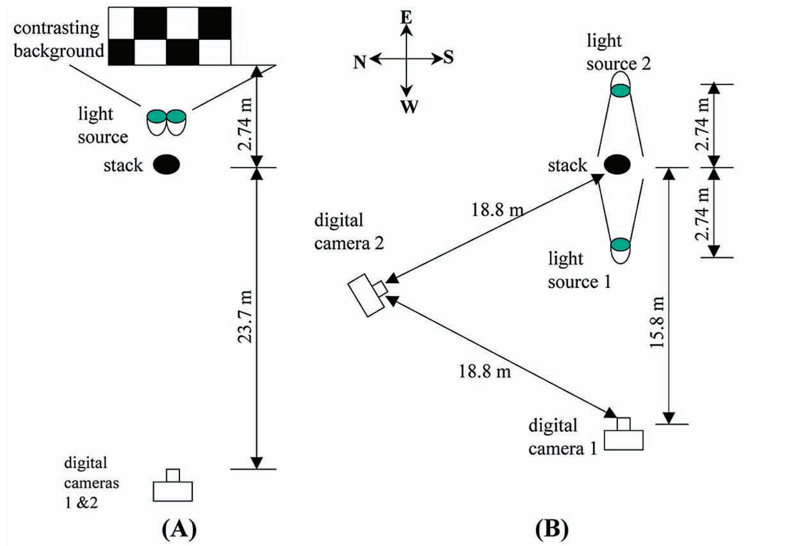
$$\text{IOE} \equiv d_i = |O_{2,i} - O_{1,i}| \times 100 \quad (15)$$

AOE is defined as

$$\text{AOE} \equiv \bar{d} = \frac{\sum_{i=1}^{N} |d_i|}{N} \quad (16)$$

where N is the total number of corresponding observations and measurements for black plumes or white plumes during the field test.

Field Test of DOM during Nighttime. A nighttime field campaign was carried out to (1) test the performance of the contrast and transmission models to quantify plume opacity during nighttime by comparing the results from the DSCs and the reference in-stack transmissometer; (2) evaluate the consistency between two different DSCs by comparing each of their opacity results; and (3) study the effect of orientation for the DSCs, light source, and stack (which is referred to as "orientation" afterward) on determining plume opacity using the transmission model. This field campaign was completed at Springfield, IL. The tests were conducted during two nights during April 2005 at an open grassland site. The sky and surrounding environment were very dark during nighttime except for the light source (Figure 5A). However, no measurements of the background lighting occurred during the field campaign. The smoke generator was operated by Illinois Environmental Protection Agency (IEPA) personnel. The stack was 4.5 m high and 30 cm in diameter. The tests started at 0% opacity and then increased to 100% opacity at 10 levels for the black plumes. White plumes were then generated with the same test sequence. The contrast model



Camera Position	Light Source Position	Scattering Angle (°)	K	
			Black Plume	White Plume
1	2	0	53.2	429.2
2	2	65	22.0	122.2
2	1	115	7.7	72.7
1	1	180	18.7	144.3

(C)

FIGURE 2. Experimental setup for testing the contrast (A) and transmission (B) models to determine plume opacity during nighttime, and the *K* values of the transmission model for the four orientations (C).

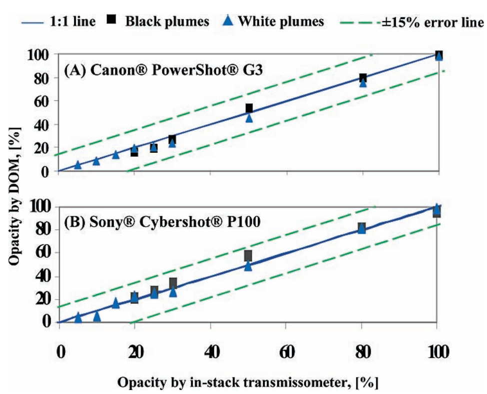


FIGURE 3. Individual opacity errors for the contrast model results for black and white plumes from the two colocated digital cameras: (A) Canon Powershot G3 and (B) Sony Cybershot P100.

and the transmission model were tested during separate days because of the different testing protocols used for each of the models as described below.

The contrast model was tested while using two light sources (500 W halogen lamps, model PAR56LB, Sound Division LC) that were set up between the stack and the contrasting backgrounds, and directed away from the plume but toward the contrasting backgrounds that were located behind and next to the plume (Figure 2A). The light sources have concave reflecting lampshades to provide collimated beams. The contrasting backgrounds consisted of eight 45 × 45 cm squares that were black and white on two square boards. Two DSCs (Canon Powershot G3 and Sony Cybershot P100) were placed at the same location that was 23.7 m away from the stack to take photographs of the plumes. The distance between the cameras and the stack was greater than 3 times the stack height and but less than 100 m to have a good view of the plumes and their immediate environment. Both cameras and the light sources were mounted on tripods and they were located 1.5 m above the ground. The cameras took one photograph every 15 s, and a total of 12 photographs were taken at each opacity level for each plume color. The opacity results from the two DSCs were then compared to each other and to the opacity results from the reference in-stack transmissometer.

The transmission model was also tested with the Canon Powershot G3 (camera 1, Figure 2B) and Sony Cybershot P100 (camera 2, Figure 2B) cameras at distances greater than three times the stack height but less than 50 m to provide a clear view the plume and negligible atmospheric extinction. The cameras were set up at two orientations with respect to the stack to study the effect of orientation on the performance of the transmission model. Two of the 500 W light sources were set up in front of and behind the stack shining toward the plume. During each test, only one light source was "on" to evaluate the influence of the orientation of the light source on DOM's method to determine plume opacity. The DSCs took one photograph every 15 s, and a total of 6−12 photographs were taken at each opacity level for the black and then the white plumes. Opacity values from the two DSCs were then compared to each other and to the opacity levels from the in-stack transmissometer.

The tests were performed from 9 pm CST to 11 pm CST on April 13, 2005 and April 14, 2005, and they resulted in 1200 digital photographs. The transmission model was tested on April 13 and the contrast model was tested on April 14. According to the hourly meteorological data obtained from Weather Underground (*17*), the wind vector was 14.8−16.7 km/h NNE during the first night and 9.3−16.7 km/h NNE-E during the second night.

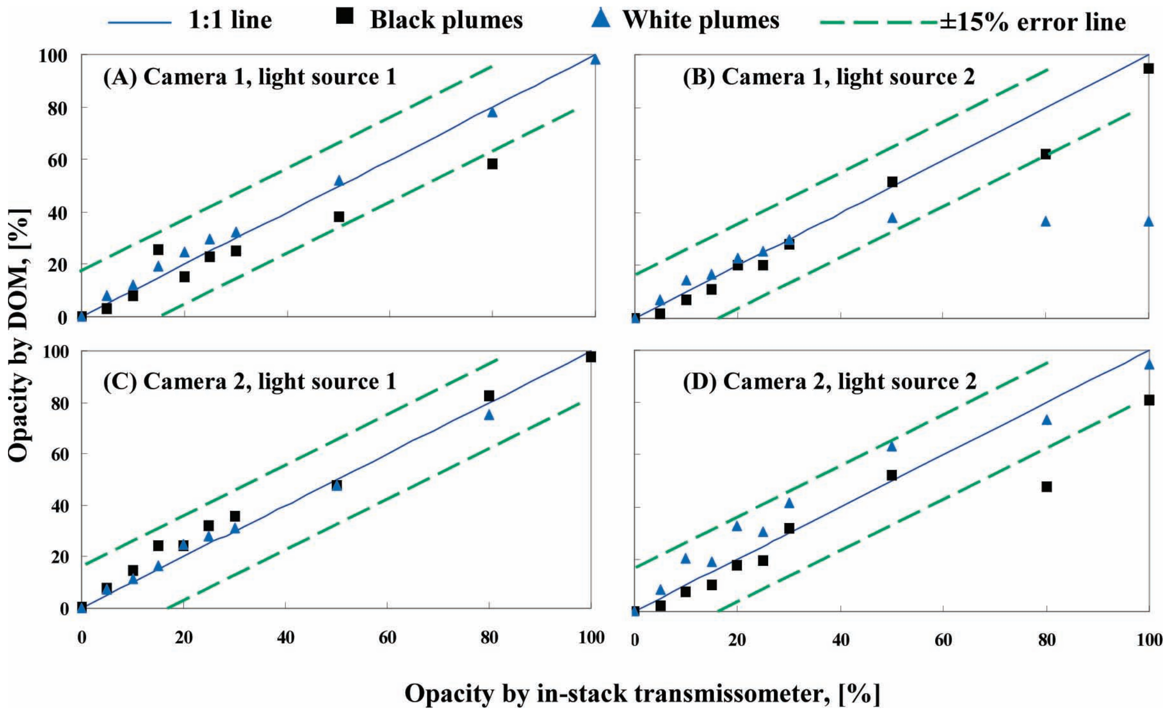


FIGURE 4. Individual opacity errors for the transmission model results for black and white plumes for the four orientations.

Results and Discussion

IOEs and AOEs of the results from both contrast and transmission models were determined by comparing DOM opacity values to the opacity values from the in-stack transmissometer to evaluate the performance of DOM during nighttime conditions. Contrast Model: All of the IOEs for results obtained with the two colocated DSCs are <15% (Figure 3). The solid line represents a perfect correspondence between opacity values determined by DOM and the in-stack transmissometer. The bold dashed lines represent IOEs of 15%. Results from the contrast model compare well to the results from the in-stack transmissometer with all IOE results ≤15% and have good linearity with R^2 values >0.98 for all linear regressions. The consistency between the results obtained with the two DSCs was evaluated by calculating AOE values using eqs 15 and 16, but the $O_{2,i}$ value used here is the result obtained with one of the two DSCs instead of the reference in-stack transmissometer. The AOEs between the two cameras are 4.3% for black plumes and 3.4% for white plumes. Paired t-tests were performed to analyze the results obtained by the two DSCs to determine if one camera's results were significantly different from the other's results. The resulting t value is 1.941 and the p value is 0.0701, which is >0.05 and suggests that the differences between the results from the two DSCs were not statistically significant from each other for both black and white plumes. The Student t-test between DOM derived opacity values (Sony camera and Canon Camera) and the in-stack transmissometer opacity values shows that DOM-derived opacity values are not significantly different from the in-stack transmissometer opacity values at the level of significance of 0.05. The t values are 2.47 and 3.43 for Canon camera and Sony camera, respectively. The corresponding p values are 0.83 and 0.99 for Canon camera and Sony camera, respectively.

AOE values for the contrast model were 2.8 and 2.9% for the black and white plumes, respectively, for Canon Powershot G3, and 3.5 and 2.3% for the black and white plumes, respectively, for Sony Cybershot P100, which are well below 7.5%. t-tests for all plume categories for the two cameras demonstrated that all of the AOEs are significantly ≤7.5% at a confidence level of 99%. The 99% confidence intervals are 0.8−4.8%, 1.0−4.8%, 1.0−6.0%, and 0.9−3.7% for these corresponding tests.

Transmission Model. During the nighttime field campaign, the property of the light source (N_L), ambient lighting condition (N_{sky}), and plume optical properties (P and ω) were assumed to be constant for black and white plumes during the three-hour test on April 13, 2005 for the transmission model. The only changeable factor was the relative orientation among the DSCs, light source, and the stack, which determines the scattering angle, θ, in eq 11 and the opacity values of the black and white plumes. K values were determined using the empirical method described earlier for the four orientations used in the field campaign and are summarized in Figure 2C. Black plumes had smaller K values than white plumes because black plumes have much smaller ω values when compared to white plumes.

The K values in Figure 2C were used in the transmission model with their corresponding orientations. Individual opacities measured by the transmission model and by the in-stack transmissometer for black and white plumes are described in Figure 4. The panels A, B, C, and D in Figure 4 are for the four orientations as described in Figure 2B. Results from the transmission model compare well to the results from the transmissometer for plumes with opacity values from 0 to 50% (Figure 4) with all of the individual errors ≤15% (88% of these errors are ≤7.5%).

For plumes with opacity >50%, especially when the plume was directed away from the light source, the brightness of the further side of the plume appeared to be reduced because of the increased optical path for the light source (not for the camera's optical path) (Figure 5A). Hence, the brightness of the plume no longer increased with its opacity as much as it did for low opacity plumes (i.e., plumes with opacity ≤50%). This resulted in a negative bias in opacity values when using eq 13. Reduced plume brightness with increased opacity results from the one-directional lighting of the plume. For example, the prevailing wind direction was NNE during the test using

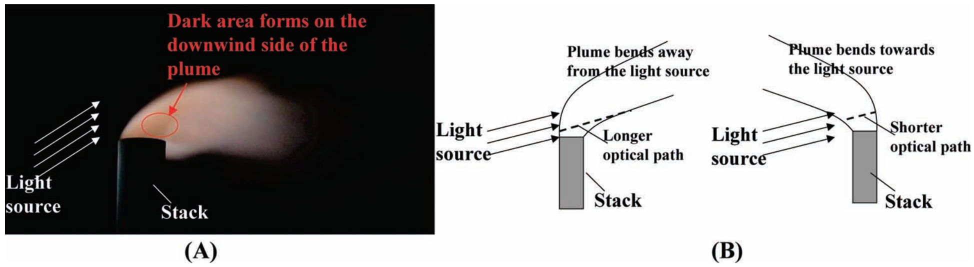


FIGURE 5. Shadow formed on the downwind side of an 80% opacity plume when the light source was on upwind side (A), and the effect of the plume bending direction (B).

the transmission model on April 13, 2005. The plumes were directed horizontally toward SSW due to the wind. If the plume was illuminated by a light source that was located upwind (e.g., light source 2 in Figure 2B), a dark area will be formed on the downwind side of the plume. On the contrary, such response will not be as apparent if the light source is located downwind of the plume and the plume passes toward the light source because of shorter optical path compared with the optical path when the plume is directed away from the light source (Figure 5B). Such behavior explains why the tests with light source 2 configuration has more results that exist outside of the error limit of ±15% for IOE values (Figure 4B and D). Assessment of the effect of wind on optical path length and opacity determination during nighttime conditions was beyond the scope of the field campaign, but would be useful to complete in the future. Further field studies and analysis of the increased errors at opacity values >50% for the transmission model are warranted. Hence, the transmission model is not recommended to be used to quantify the opacity of plumes for values >50% during nighttime at this time. In addition, the light source should be set up downwind of the plume to minimize the shadowing of the plume.

The IOE values associated with the opacity values obtained with the transmission model and the transmissometer for opacity values ≤50% are 0−14% for the four orientations. Results from the transmission model have good linearity with R^2 values >0.89 for all linear regressions with opacity values ≤50%, which suggests that the transmission model has very good precision when determining the opacity of plumes that are ≤50%

The AOEs for results from the transmission model when compared to the transmissometer for all of the orientations were 2−7.6% for the four orientations for plumes with opacity ≤50% (Figure 6). AOEs of 4.7 and 2.8% for camera 1 and 4.5 and 2.0% for camera 2 were obtained for black and white plumes when the light was located downwind of the plume, while AOEs of 2.4 and 2.9% for camera 1 and 2.8 and 7.6% for camera 2 were obtained for black and white plumes when the light source was located upwind of the plume. Again, the AOEs for all of the tested plumes (0−100%) are larger than those for plumes with opacity ≤50% as described by the aforementioned discussion, especially when the light source was located upwind (i.e., light source 2).

Discussion of Results from Both Models. The contrast model and transmission model of DOM were adapted to quantify plume opacity during nighttime. IOEs and AOEs for the contrast model are ≤15 and 7.5% for both black and white plumes for all opacity values, respectively. IOEs and AOEs for the transmission model are ≤15 and 7.6% for black and white plumes with plume opacity values ≤50%, respectively. The extinction of high opacity plumes limits the perceived brightness of the plume with opacity values >50%, which results in negative bias when using the transmission model. The orientation of the light source

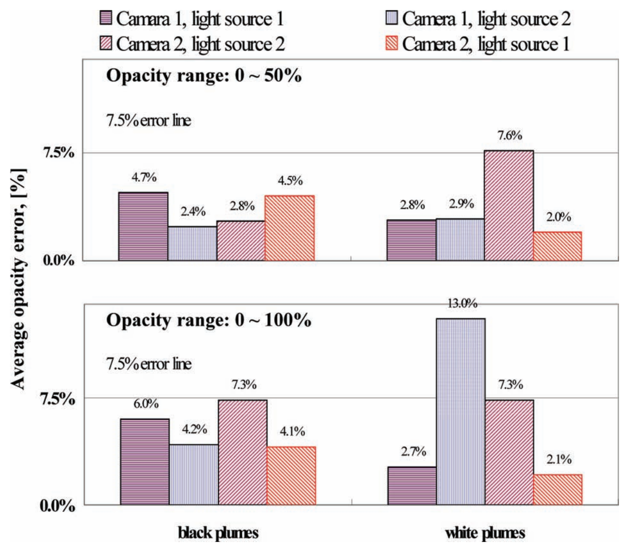


FIGURE 6. Average opacity errors for the transmission model results for black and white plumes for the four orientations.

with respect to the stack and camera also affects the results for the transmission model. Field results show that stronger light scattering signals were obtained when the light was located to the back of the plume and resulted in a higher accuracy for transmission model. As demonstrated in this paper, DOM has the ability to quantify plume opacity during nighttime with an accuracy of IOE ≤ 15% and AOE ≤ 7.6% for plumes with opacity values ≤50% for the conditions tested during the nighttime field campaign.

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